

8821

NAGW-528

Theoretical Study of the X-ray Emission from
Astrophysical Shock Waves

Grant NAGW-528

Semiannual Progress Reports No. 4 and 5

For the period 1 June 1985 through 31 May 1986

Principal Investigator

John Raymond

June 1986

Prepared for
National Aeronautics and Space Administration
Washington, D.C. 20546

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

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(NASA-CR-177318) THEORETICAL STUDY OF THE
X-RAY EMISSION FROM ASTROPHYSICAL SHOCK
WAVES Semiannual Report, 1 Jun. 1985 - 31
May 1986 (Smithsonian Astrophysical
Observatory) 9 p HC A02/MF A01

N86-27176

CSCL 03B G3/93

Unclass
43424

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INTRODUCTION

Theoretical X-ray emission spectra are needed to interpret the X-ray emission observed by many low and moderate resolution X-ray instruments, and to provide diagnostics of physical conditions for high resolution spectra. Over the past decade, we have developed a set of model codes which compute the X-ray and XUV emission for a wide set of physical conditions, including high or low densities, photoionized gas, and time-dependent ionization balance. In the past year, we have continued to improve the atomic rate coefficients in the code, we have added some further capabilities, and we have applied it to several astrophysical problems.

ATOMIC RATES

Our synoptic study of the excitation of Fe XVII was published (Smith *et al.* 1985), and a detailed investigation of temperature sensitive Fe XVII line ratios was accepted for publication (Raymond and Smith 1986). We found that the effects of autoionization to excited levels on dielectronic recombination rates had been badly overestimated by previous authors. We also found that resonances in the excitation cross sections dominate the excitation of the strong 17 \AA 3s lines. The predicted line ratios were consistent with line ratios observed by the *Einstein* FPCS from the supernova remnant Puppis A, but the uncertainties in the measured line ratios and in the intervening column density N_H precluded useful determination of the electron temperature of the emitting gas. In comparing the predictions with solar observations, we found that care must be used in defining how "observed" line fluxes are measured, in that dielectronic recombination satellites may or may not be included in the measured flux. The observed $4d / 3d$, $3s / 3d$, and satellite / $3d$ line ratios for active regions all agree with predicted line ratios within the uncertainties in

measured ratios and temperature of the emitting gas, but the ratios imply somewhat different temperatures. We showed that this is largely a result of the differently weighted averages which each line ratio reflects. Figure 1 shows the predicted 3d / 3s ratio as a function of T for low resolution (including all satellites and the full 3d multiplet; top curve), moderate resolution (including the satellites having $n' > 3$ and only the resonance 3d line; middle), and including no satellites at all (bottom).

We have also compared the XUV emission predicted by the code with observations of a large plume above a sunspot (Doyle *et al.* 1985). Since many lines were observed and the instrument calibration was reliable, this is an excellent test of the model code. We also measured several temperature sensitive line ratios. The temperatures indicated were lower than those seen in the quiet sun, suggesting a departure from ionization equilibrium consistent with radiative cooling. We computed the emission spectrum for gas cooling from a little below 10^6 K, and this spectrum can be used for a variety of astrophysical objects,

Non-Equilibrium Cooling Rates

B. Smith visited Cambridge in January and May, and we computed cooling rates for each ion of the dozen most abundant elements over the full temperature range 10^3 K - 10^8 K for a set of densities from the low density limit to 10^{12} cm⁻³. We plan to present a set of fits (some of which we have already completed) for use in hydro codes. The fits will encompass varying degrees of complexity, allowing appropriate choices for the tradeoff between accuracy and computer time to be made for specific problems. These will include ionization equilibrium, the ionization balances appropriate for isochoric and isobaric radiative cooling, cooling as a function of average charge of oxygen, cooling as a function of average charge of each element,

and detailed cooling for each individual ion. We intend to apply these cooling rates in hydrodynamic calculations of shock waves in O star winds.

Supernova Remnants

We have begun a collaboration with M. Arnaud and R. Rothenflug of CEN-Saclay to compare *Einstein* HRI and *EXOSAT* CMA images of the Cygnus Loop. The energy bands observed by these instruments are enough different that the ratio will be quite temperature sensitive. We will look for temperature variations with radius and temperature variations associated with individual features, such as clouds struck by the blast wave. We have observed faint H α filaments of the non-radiative shock at the NE edge of the Cygnus Loop (Hester, Raymond and Danielson 1986), and we are now comparing the HRI and optical images to investigate the possible role of clouds in producing the observed morphology. As noted above, we have analyzed *Einstein* FPCS spectra of Puppis A.

Cataclysmic variables

Two studies of X-ray emission from cataclysmic variables were published (Patterson and Raymond 1986a,b). One dealt with hard X-ray emission from high \dot{M} systems, and the other dealt with soft X-ray emission. We studied the structure of the boundary layer and reprocessing of both hard and soft X-rays by the white dwarf surface and by the disk. Unlike other recent studies, we found that the lack of detection of old novae in X-rays can be entirely attributed to the extreme softness of their spectra and the substantial N_H which the X-rays must traverse. In a closely related study supported by IUE Guest Observer funding, we have computed the effects of boundary layer emission on the ionization state and P Cygni profiles of the

winds of high \dot{M} cataclysmic variables (Mauche and Raymond 1985; Raymond and Mauche 1985).

Shock Waves in O Star Winds

A detailed study of shocks in O star winds was published (Krolik and Raymond 1985). We computed the driving force due to radiation pressure in spectral lines and the X-ray emission spectra for a grid of shock velocity and swept up column density for conditions appropriate to an O star wind. Figure 2 shows the X-ray spectrum produced by a 500 km/s optically thin shock. While the results basically confirm that such shocks are capable of accounting for the observed X-ray luminosities and temperatures, a definite prediction awaits a detailed treatment of the intershock region. We have therefore begun to modify a hydro code for application to this problem.

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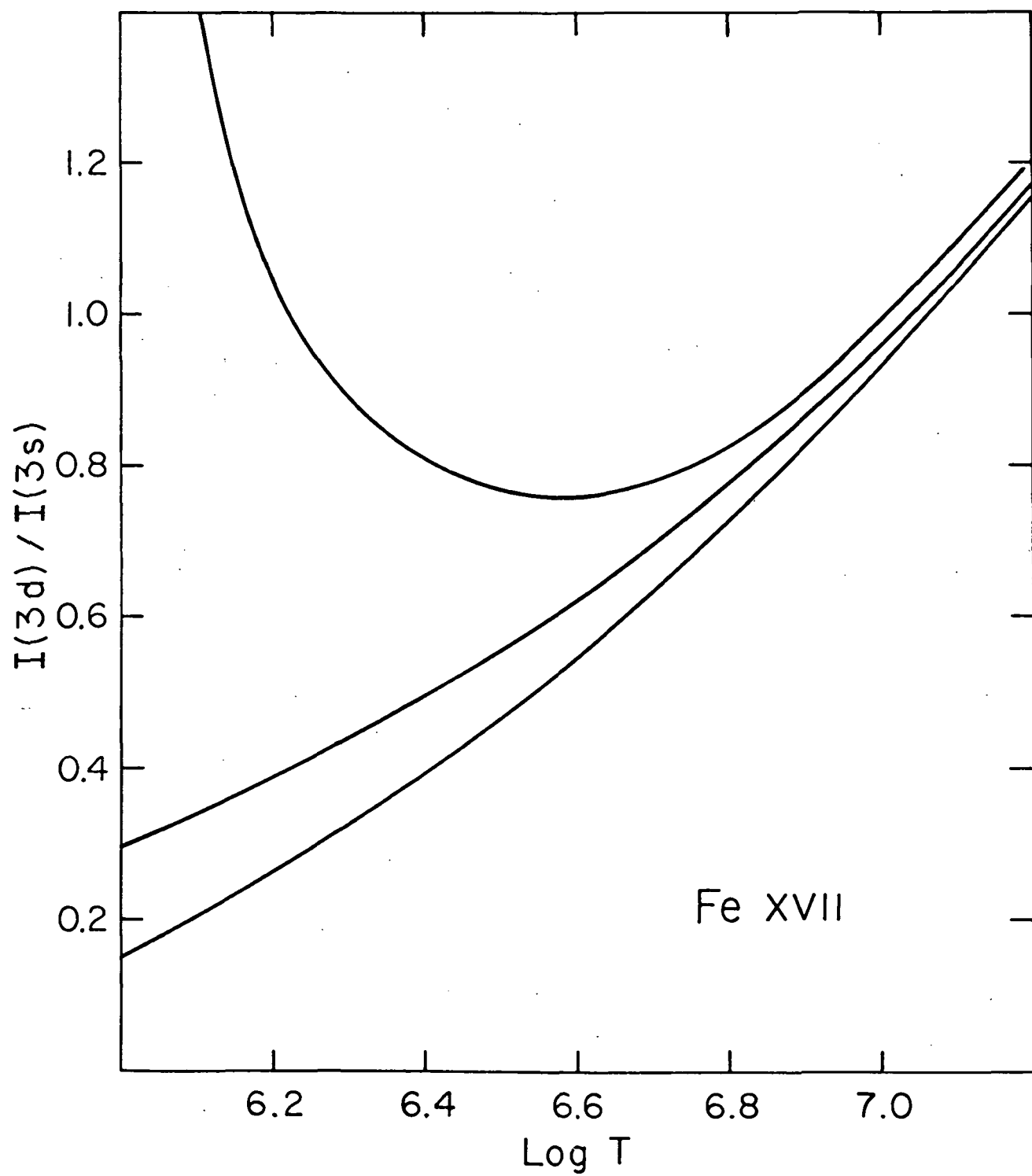


FIGURE 1

FIGURE 2

